Measurement of Coherent Cherenkov Radiation from an Intense Beam of a Picosecond Electron Bunch

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High-intensity Cherenkov radiation (CR), emitted in air from a high-current 30-MeV electron bunch (2×10^{11} electrons/bunch) of the linear accelerator at the Institute of Scientific and Industrial Research, was observed at wavelengths from 0.4 to 3 mm. The radiation was emitted at an angle of 38 mrad, with some spread, from the beam axis. The radiation measured was about 10^{11} times as intense as that calculated for ordinary CR. Such enhancement is attributed to the coherence which appears in CR emitted from electron bunches of relatively short length.

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Cherenkov radiation (CR) is emitted when high-energy electrons pass through a dielectric material under the condition $\beta n > 1$, where β is the ratio of the velocity of the electron to that of light in vacuum and n is the refractive index of the medium. Polarized radiation which has a broad spectrum is emitted directionally around the path of the electron at a certain angle, forming a so-called Cherenkov cone, where the angle θ is given by $\cos\theta = 1/\beta n$.[1] The number of photons emitted from the electron between wavelengths of λ_1 and λ_2 is expressed as

$$N = 2\pi\alpha l\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)\left(1-\frac{1}{\beta^2 n^2}\right), \qquad (1)$$

where α is the fine-structure constant ($=e^2/\hbar c = 1/137$) and l is the path length of the electron in the medium. In general, CR has been used as an intense light source from the ultraviolet to visible. Infrared light is comparatively weak in CR because the intensity of the CR for a unit wavelength of the bandwidth decreases with increasing wavelength, as expected from Eq. (1).

Cherenkov radiation from an electron is essentially coherent. The work "coherent" in this paper means a mutual effect among electrons in an electron bunch. It was predicted theoretically that for wavelengths equal to or longer than the length of the electron bunch the radiation is coherent and, hence, highly intense.[1] If the whole radiation from the electrons in a bunch becomes coherent, the intensity of the radiation evaluated from Eq. (1) might be increased by a factor equal to the number of electrons in the bunch. To our knowledge this phenomenon has not been observed experimentally. The present work has been performed to observe the effect of coherency on CR. For synchrotron-radiation (SR) coherence due to a similar effect the case of short bunch length has been investigated[2] and observed experimentally.[3,4]

The 38-MeV L-band electron linear accelerator (linac) of the Institute of Scientific and Industrial Research (ISIR), Osaka University, produces intense single-bunch beams. The linac is equipped with a high-current electron gun, a specific buncher system which consists of three subharmonic prebunchers and ordinary bunchers, and a bunch compressor. The bunch length can be changed from 9 to 50 ps by controlling the conditions of the bunchers and the bunch compressor. The details of the apparatus have been described elsewhere.[5–7] The characteristics of the single-bunch beams are as follows: The total charge of electrons in a bunch is 67 nC (4×10^{11} electrons) at maximum; the beam diameter is 3 mm or less; the energy spread is from 0.7% to 2.5% over the range of 24–35 MeV; and the repetition rate of the bunch is from 1 to 720 s^{-1}. In this study 30-MeV single-bunch beams have been used. The total charge of electrons in a bunch and the half-maximum pulse width of the bunch are 30 nC and about 30 ps, respectively.

The experimental setup for measuring the radiation is schematically shown in Fig. 1. Electrons accelerated are

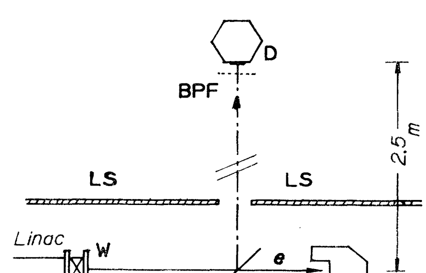

FIG. 1. Schematic diagram of the experimental setup (BCM denotes beam current monitor, M denotes Au surface mirror, BS denotes beam stopper and current monitor, LS denotes light shield, BPF denotes bandpass filter, D denotes detector of Si bolometer for far-infrared light, and W denotes Ti-foil window).

extracted from a vacuum into the air atmosphere through a Ti-foil window. Cherenkov radiation from the electrons passing in air for a length of 50 cm are reflected to a detector with a plane mirror coated with Au on the surface. There is enough space around the path and from the geometry it is estimated that possible sources of radiation are CR and bremsstrahlung. The electron beam diverges to some extent according to the scattering in the Ti window and in air. The divergence angle had been obtained from the beam profiles measured with film dosimeters and had been less than 15 mrad. This causes the divergence of the radiation to be at nearly the same angle.

The detector is a liquid-He-cooled Si bolometer with a bandpass filter for wavelengths between 0.1 and 3 mm. The spectrum of the radiation has been measured using a mesh metal bandpass filter for 1–1.4 mm, and glass-bead composite bandpass filters for 0.4–3 mm. The sensitivity of the detector has been evaluated at a wavelength of 1.18 mm with light from a high-pressure Hg lamp of 3800 K.

The angular distributions of the radiation have been measured by changing the angle of the mirror reflecting the radiation to the detector. The change in the intensity of radiation due to the change in beam conditions during the measurements is estimated to be within 5%. Measurements have been made for the vertical and the horizontal distributions and the results obtained have shown similar behavior. Figure 2 shows the horizontal distributions measured for two bandwidths of wavelengths. In this figure, one can clearly see the radiation cones, which offer evidence for CR. The spread of the cone angle about the peak for the upper curve is larger than that for the lower curve. The cone angle for the peaks of the lower curve can be evaluated to be 38 ± 2 mrad. From this value the refractive index can be calculated to be 1.0008, according to the expression for the Cherenkov angle described before. This is larger than the index of standard air for visible to infrared light, 1.0003.[8] However, there are no useful data in the far-infrared region for the present wavelengths.

Figure 3 shows the spectrum of the radiation measured, and that of the ordinary CR calculated according to Eq. (1) for comparison. When radiation becomes coherent the intensity of the radiation could be increased by a factor equal to the number of electrons in the bunch, as mentioned before. Such large enhancement is observable in the results for the present experiments, as shown in Fig. 3. The discrepancy between the results for the measurements and for the calculation is probably due to the fact that the wavelengths are shorter than the present bunch length (9 mm). For wavelengths shorter than the length of a bunch, the coherence is incomplete and, hence, the intensity of the radiation might be affected by the size of the bunch and by the distribution of electrons in the bunch. We now consider the radiation of the wavelength λ from the electrons distributed uniformly in a bunch larger than λ in size. If it is assumed that the CR from the electrons in each cube of the side of λ are coherent, the intensity of radiation given by the sum of these coherent CR would be proportional to λ^3. Such qualitative estimation has been made to evaluate

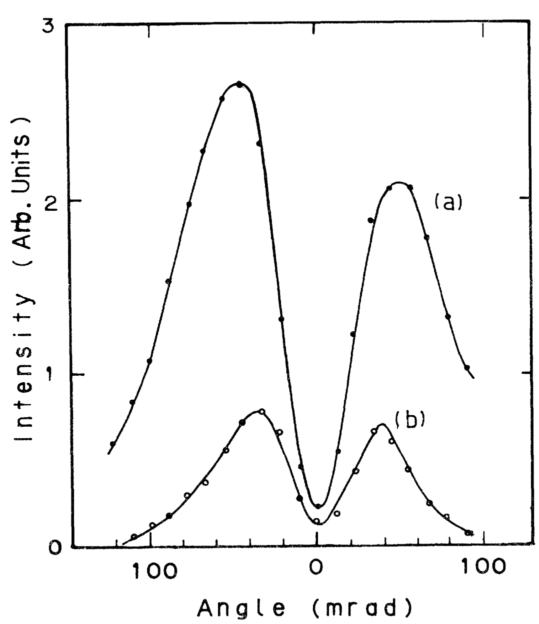

FIG. 2. Relative angular distributions of the CR measured for bandwidths of (a) 0.4–3 mm and (b) 1–1.4 mm.

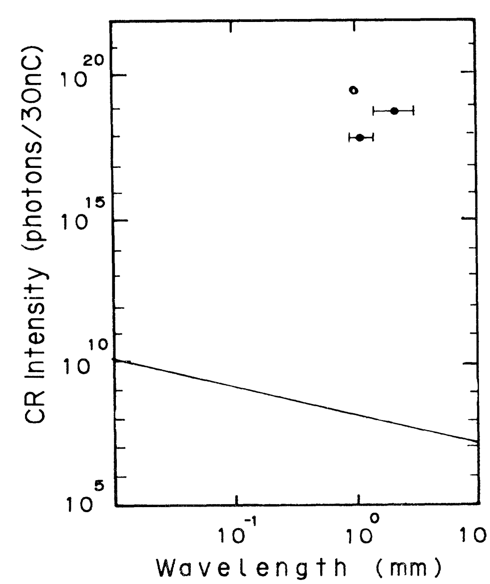

FIG. 3. The intensity of the CR measured for the bandwidths indicated with horizontal bars, the spectrum calculated according to Eq. (1) for 10% bandwidth (solid line), and the intensity expected for the complete coherence over the bunch for 10% bandwidth (open circle).

the spectra of coherent SR.[9]

For applying the coherent CR to light sources in far-infrared regions, the formation of the Cherenkov cone is an important feature. It is possible to collect all the radiation onto a relatively small area by using a concave mirror. The intensity of the radiation increases with increasing the path length of the electron beam in air. For path lengths of 1 m or so, the dispersion of the beam in air is not remarkable.

The ISIR linac has the specific buncher system described before. With this system the size of the electron bunch and the distribution of electrons in the bunch can be changed. For further study of the radiation processes, the relation between these factors of the bunch and the spectrum of the radiation should be investigated. We are planning to perform measurements of the spectra over wavelengths of 10 μm to 3 mm with Martin Puplett spectrometers.

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